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Innovative planning and evaluation system for district heating using waste heat considering spatial configuration: A case in Fukushima, Japan

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ABSTRACT

Energy shortage and global climate change have created a dilemma in Japan, especially after the great earthquake of 2011 in eastern Japan. District Heating System (DHS) using waste heat is highlighted as an attractive solution. However, because of low heat demand in urban areas and the geographic separation of industries, popularizing this solution is considerably difficult in Japan. Previous studies have focused on technical improvements on existing district heating networks, but these studies lack sufficient discussion on an early-stage integrated land-use planning. Supported by technological assessment and emerging concepts of Industrial-Urban Symbiosis (I-US), this study combines the system development of DHS and land use scenarios into a symbiotic design based on inventory survey and geographic database, and conducts a cost-benefit analysis to scientifically and quantitatively evaluate the effects brought from land-use policies. Results from a case study of Shinchi Town in the Fukushima Prefecture indicate DHS using waste heat can realize significant benefits of energy saving and CO_2 reduction, provided positive guidance on land use planning is implemented. Moreover, the model framework of this study also supports a quantitative assessment on policy implementation to help in decision making on urban sustainable energy planning.

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1. Introduction

Energy shortage and global climate change have created a dilemma in Japan, especially after the great earthquake of 2011 in eastern Japan. It is accepted worldwide that distributed energy systems such as the District Heating System (DHS), which is connected to reuse waste heat sources and renewables, is an attractive solution and is of increasing importance (Hayashi and Hughes, 2013; Rezaie and Rosen, 2012).

In Europe and North America, long-term practices have indicated that DHS has a higher efficiency energy usage when compared to Individual Heating Systems (IHS). The benefits from the scale effect of heat production through the development of efficient processes and the convenience of accessing local waste heat and renewables are the main reasons for this trend giving rise to what is known as Fourth Generation District Heating (4GDH) (Morandin et al., 2014; Zhao et al., 2014). This future DHS technology is expected to play an important role in a low-carbon sustainable energy system, which involves facing the challenges of combining multi-sources and distributed generation technologies and integrating these with smart energy systems (Ivner and Viklund, 2015; Lund et al., 2014). Nowadays, the trend to improve the District Heating System is spreading all over Europe, such as the Heat Roadmap Europe project and the STRATEGO project (Enhanced Heating and Cooling Plans in EU), through which most of the European cities aim to realize a citywide integrated district heating and cooling system in the near future (Connolly et al., 2014; Persson et al., 2014).

By contrast, there are only few cases of such district heating in Japan, only located in several large cities and that function as a small-scale enterprises. Compared to the popularity of this system in European countries (e.g., 58% in Denmark, 48% in Finland, and 12% in Germany), Japan is very far behind (1.2%) (JES, 2008). The

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main reasons for this are thought to be not only the relatively warm climate but also the slowdown in urban infrastructure development and building refurbishment. The dispersed market scale and management, competition with high efficiency individual heating, and languishing support policy are also some of the causes (JHSBA, 2011). However, existing DHS in Japan still realizes an average of 20.6% reduction in primary energy consumption compared to individual heating (METI, 2008). However, Japan also generates a large amount of unused heat estimated at approximately 6000 PJ annually from general waste incineration, factories, thermal power plants, sewage systems, oceans, and rivers (Fig. 1). This quantity surpasses the total energy consumption for heating civilian spaces and hot water generation (approximately 5000 PJ) (JES, 2011). Promoting DHS using waste heat countrywide has great potential for energy saving and reduction of CO_2 emission.

As far as the proportion of unused heat is concerned, waste heat from factories and thermal power plants are the major sources of unused heat. Most of these factories and power plants are concentrated in the Tokyo Metropolis area, Aichi and Fukushima Prefecture, and depend on the availability of large energy industry groups. Recently, due to the increasing concerns about climate change and energy saving in Japanese society, district heating has been popularized in many densely populated areas of the Tokyo Metropolis. However, in colder areas such as Fukushima Prefecture, the development of district heating has languished for decades (currently only one project of DHS is located in Fukushima). With the progress in revitalization after the earthquake in eastern Japan, the timing is just right to introduce DHS that helps in utilizing the excessive waste heat. This energy saving would significantly support socioeconomic development and bring about environmental improvement.

Comparing the geographic conditions of Fukushima with Tokyo Metropolis, there are mainly two factors that are responsible for this difference in the popularization of DHS. One is the linear heat load (total heat load divided by pipeline length) and the other is the geographic proximity with waste heat sources. The former usually implies the efficiency of district heating, while the latter implies the cost incurred to access the various heat sources. Because of the low population density and the geographic separation between urban and industrial areas as a result of urban planning, it is necessary to explore a way to circumvent these two problems.

According to previous studies, the mainstream solution for extending DHS is to introduce new technology and system optimization to enhance the district heating network. Researchers are focusing on system design to combine the various resources and cogenerate so as to form a multisource distributed energy system. The *low-temperature* and *low-energy* DHSs are specific for low-density cities. For instance, Fang et al. (2013) discuss the technical feasibility of recovering low temperature waste heat from industry to urban areas through district heating. They identify the process and provide a method to estimate the potential for reuse of industry-based waste heat and evaluate a low-temperature District Heating System in northern China. Their results show that such a system not only improves the thermal energy efficiency of factories but also reduces cost, pollution, CO_2 emission, and water consumption. Moreover, Brand et al. (2012) describe several practical approaches to reduce the supply temperature of DH as much as possible by connecting with local unused heat sources such as latent heat of rivers and underground soil. Similar studies have been conducted worldwide (Broberg et al., 2012; Kapil et al., 2012; Li and Svendsen, 2012; Ostergaard and Lund, 2011; Sun et al., 2014). Other researchers such as Chae et al. (2010), Dalla Rosa and Christensen (2011), Dalla Rosa et al. (2012), and Tol and Svendsen (2012) focus on support-system optimization techniques such as introducing twin pipelines, layout of a *T-connection* network, and smart flow rate control to further improve the efficiency of DHS. These technical improvements are considerably effective in districts where DHS is already popular and serve to further extend its application by increasing the competitiveness of DHS *vis a vis* individual heating. However, without a reform in urban planning, the expected improvement of the system is considerably limited.

By contrast, on the basis of technology assessment, material and energy flow analysis, and the Life Cycle Assessment (LCA) method, the emerging Industrial Symbiosis (IS) breaks the bottleneck of simplex technical path that focuses on optimal technology integration and combination of spatial elements. From the perspective of industrial ecology, IS supports a systemic analysis and design process for promoting the exchange byproducts including material, energy, and water, to enhance the competitive advantage through process synergy and cooperation between industries (Chertow, 2000; Dong et al., 2013; Olsson et al., 2015; Park et al., 2008). Its extended version, known as Industrial-Urban Symbiosis (I-US), focuses on utilizing waste heat starting from municipal solid waste incinerators to industries and recovering low temperature waste heat from industrial process to urban areas (Fig. 2) (Dong et al., 2014; Van Berkel et al., 2009). On the basis of a technical assessment

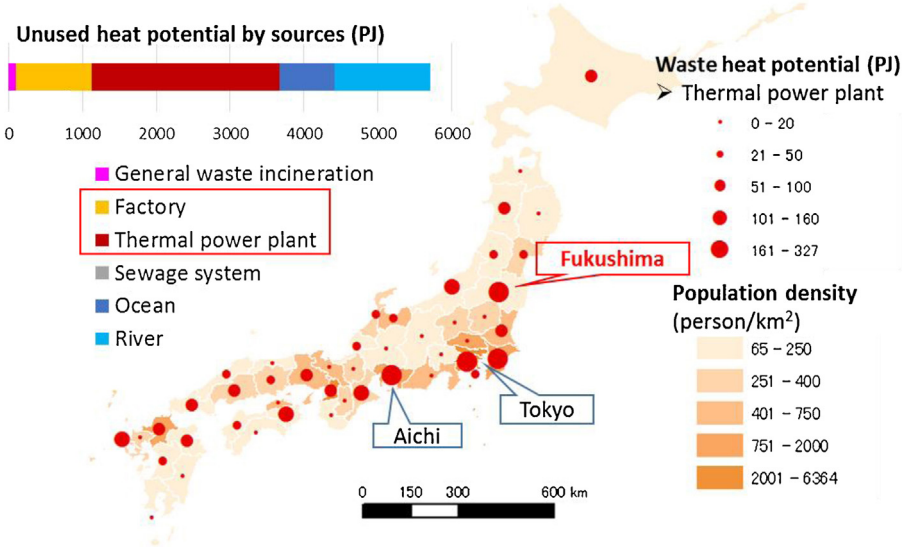

Fig. 1. Annual unused heat potential by sources and distribution of power-plant-based waste heat potential in Japan. Data source: JES (2011).

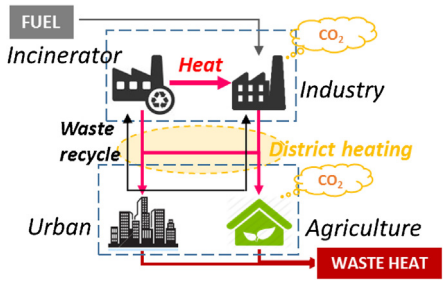

Fig. 2. Industrial-Urban Symbiosis between industry, urban and agriculture.

and a symbiotic design, I-US provides a philosophy and a state-of-the-art system for trial in actual industrial and urban planning (Jacobsen, 2006). Through the application of I-US, DHS, which uses waste heat, has a great potential for efficiency improvement and can be popularized.

With the development of GIS (Geographic Information System), it becomes much easier to grasp the precise spatial distribution of the heat demand density (Schorah, 2014). Also, the location of local existing and emerging heat sources and sinks can be precisely identified by programming (Finney et al., 2012a, 2012b). These maps of heat demand and supply, the *Heat Atlas* provide very detailed information to help in evaluating the feasibility of introducing DHS and investigating the most cost-efficient system design. So far, land use has been formally identified to be a crucial factor impacting urban energy planning and this parameter needs to be quantified in the optimization models. Nowadays, the first step in energy planning is to conduct an inventory of regional resources and demand by GIS analysis, and embed the overall geographic information into a linear programming model for technical assessment (Girardin et al., 2010; Nielsen and Moeller, 2013). Consequently, there are several studies being carried out that focus on conducting spatial planning to optimize the civilian utilization of waste heat in the field of energy symbiosis (Togawa et al., 2013, 2014). Since GIS is closely related to land use planning, combining technology assessment with symbiosis design and evaluation by GIS spatial analysis will be of increasing importance for promoting waste heat utilization.

In this context, the present study aims at filling the research gap in two fields. Firstly, we propose to provide a model framework including geographic analysis, system design and land use scenarios for studying the effects of urban planning on energy symbiosis. Secondly, the typical case of a low density city has been studied and considered as an example for the quantitative assessment of land use policies. The knowledge thus gained will be an important tool to support decision making on planning DHS using waste heat. In summary, this study aims to combine the system design of DHS and land use scenarios with a symbiotic design based on inventory survey and geographic database, and conduct a cost-benefit analysis to scientifically and quantitatively evaluate the influence of land use policies.

In a first stage, this study evaluates the cost-benefit of economy and environment, while temporarily excluding the actual negotiation process and governmental regulation such as taxes, subsidies, as well as the fluctuation of energy price, interest rate and technology diffusion. Land use is assumed to be a modifiable factor while the other factors are considered as external factors. With these assumptions, the following section (Section 2) introduces the basic information premises and survey results from a case study, Section 3 describes the interpretation of the models and scenarios developed herein, Section 4 presents the results of the estimation and discussion and finally, Section 5 summarizes all the findings in the form of a conclusion.

2. Survey on heat sources and heat demand

2.1. Shinchi town

This study considers Shinchi Town in the Fukushima Prefecture of Japan as a case study area, which has been selected as a future hub of energy resources and as a pilot area of the "Environmental Future City" national project of Japan. As shown in Fig. 3, Shinchi Town is not a large city, and is located in the northeast part of the Fukushima Prefecture. Its total land area is only 46.35 km^2 with a population of 8000 as determined in 2014. In the same year, Shinchi Town achieved a GDP of 46.18 billion yen, for which the primary, secondary, and tertiary industry contributed 1.4%, 26.8%, and 71.8%, respectively (PBS, 2015). Most of the land in the western area is mountainous being covered by forest, while the eastern part is made up of mainly agricultural land. Residential buildings are located dispersedly along the main national and local roads. Three areas where residences were concentrated could be identified from the map, namely Shinchi Station area, Komagamine area and Fukuda area. Shinchi Station area is the town center and is the transit point for the Joban Rail. In the vast farmland area, cultivation of plants (principally greenhouse type allowing irradiation by sunlight) is rapidly becoming popular. In the southeastern part, Shinchi Town shares a large industrial park (Soma Central Industrial Park) with Soma City, in which many factories, such as large scale thermal

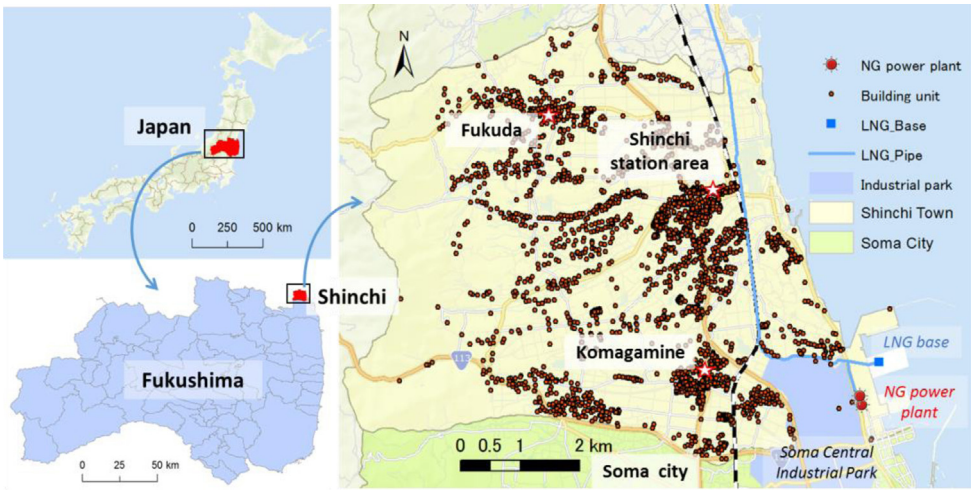

Fig. 3. Location of Shinchi Town and building distribution.

power plants, ceramic, chemical and non-ferrous manufacturers, are located.

Unfortunately, during the 2011 earthquake, the coastal area of Shinchi Town was destroyed and had hundreds of victims. In view of a long-term reconstruction, several large scale projects are just in planning and implementation stages, including a large scale LNG base and an advanced natural gas thermal power plant, which are located in the industrial park. Benefitting from the industrial development plan, Shinchi Town aims to attract a population of about 2000 by 2050. To combine the benefits of economic growth and environmental improvement, in addition to improving the regional attractiveness for living, will be a long-term issue for local governments. As a part of this project in Shinchi Town, this study aims at providing an environment-oriented solution based on I-US for Shinchi Town's sustainable urban development. For designing the symbiosis network, we have conducted several surveys to capture the local characteristics of energy sources and demand in Shinchi.

2.2. Survey on waste heat sources

Quality and available quantity of waste heat from the sources is a key factor for energy symbiosis network design (Morandin et al., 2014). Through a series of surveys and negotiations with local government and companies, we propose to identify and provide a detailed and quantified data on local characteristics of the waste heat potential and demand. The results of the heat source survey in Soma Central Industrial Park are mapped in Fig. 4. Currently, the available sources include two large scale thermal power plants and several factories.

With respect to the quality, industrial waste heat has a higher quality for district heating because this value can be adjusted to match the requirement without using technologies such as heat pumps. In another parallel study, we at first designed a network of Industrial Symbiosis which extracts steam from the turbine of the thermal power plant (more than 200 °C) to provide heat for a factory process. In the second stage, for cascading using the waste heat, we propose to recover the waste heat from the exhaust gas in the power plant's chimney and from the industrial processes of factories. The former can provide heat to raise temperatures of water up to 100 °C, while the latter exhaust gas up to more than 200 °C (JES, 2011; Togawa et al., 2014). Both these temperature values are above the temperature requirement of district heating (averagely 80 °C) (JIE, 2008).

In parallel, we also surveyed the available quantity of waste heat that can be provided by target companies. Although both the thermal power plants can be at 1000-MW level for recovering waste heat from the exhausted gas, considering the difficulty in introducing a heat exchanger in the existing system and the possible impacts on surrounding environment, at the current stage, the companies agree that with a very conservative supply quantity, the coal-based thermal power plant can supply 40 TJ, while the one based on natural gas can supply 20 TJ annually. However, taking the results from a survey on the energy input for production, we also estimated the waste heat potential from factories by a method taken from JES (2011). The result shows that the ceramic factory has the largest potential of 32 TJ, while the others have less than 10 TJ annually. Since the large suppliers are concentrated in the center of the industrial park currently, we propose to utilize the waste heat from the two power plants; the ceramic factory and the nearby chemical factory. With the progress of this project, in the future, there is a possibility to encourage factories to increase the waste heat supply once the benefits are actually realized through the implementation of the project.

2.3. Survey on heat demand

On the demand side, the waste heat is proposed to be introduced into surrounding urban area for ambient heating and hot water. Based on building point data, we apply a method using building type and floor area information for estimating annual heat demand for each building (see Appendix a). As shown in Fig. 5, the total annual civilian heat demand for space heating and hot water is about 160 TJ, concentrated mainly in two areas, named Shinchi Station area and Komagamine where possess a half as 80 TJ. By spatially joining them into 100 m grids, we mapped the heat demand distribution. Learning from the distance analysis along the road network, since there is no existing infrastructure for DHS and considering the limitation of initial investment and the scale of the project, Komagamine area (within 3 km to heat sources) is chosen as the target area herein. However, the annual heat demand covered in this area is merely 24 TJ, which is much lower than supply potential.

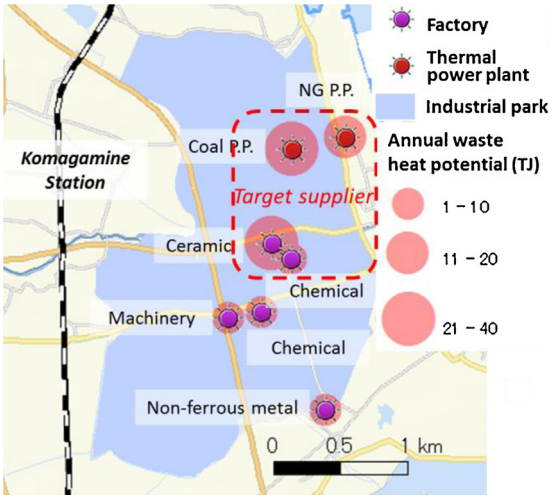

Fig. 4. Location of waste heat sources and potential.

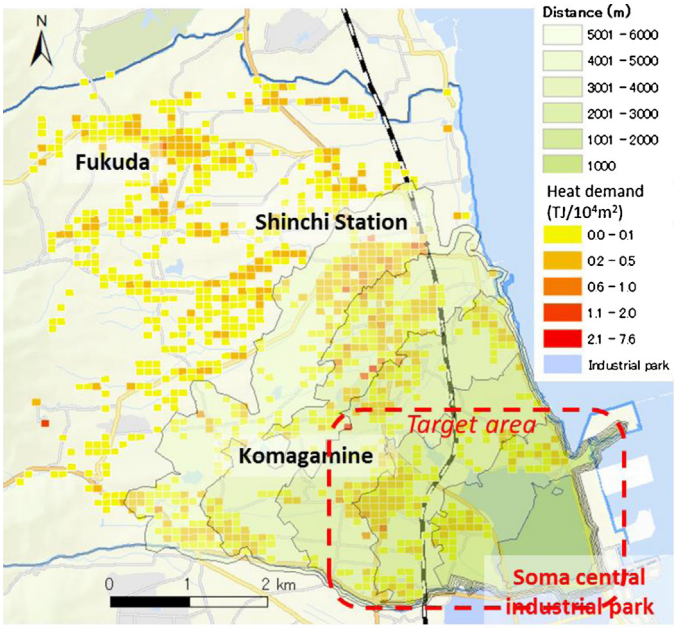

Fig. 5. Heat demand distribution and distance analysis.

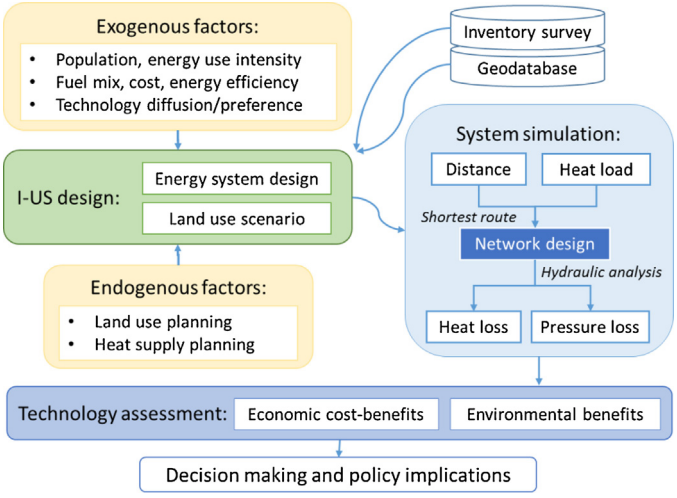

Fig. 6. Model framework and assessment process.

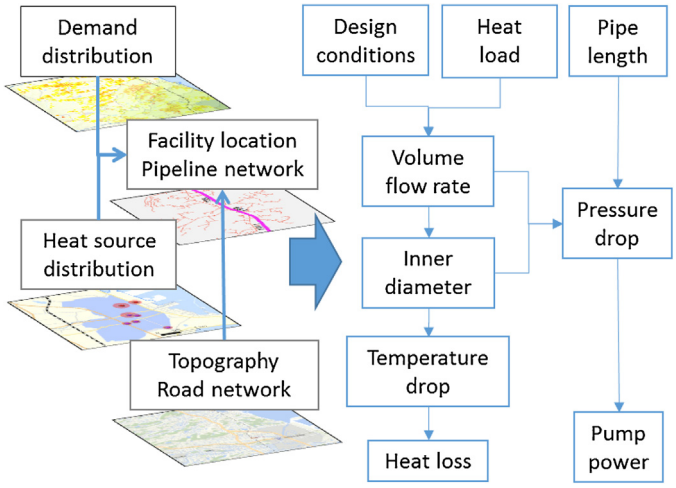

Fig. 8. Model for pipeline network design and evaluation.

3. Model development and assessment

3.1. Model framework

To embed and highlight land use planning as a critical tool for realizing DHS using waste heat, we developed a model framework as shown in Fig. 6. On the basis of inventory survey on waste heat supply and demand distribution, a district heating network is designed and optimized for adapting to the peak season heat demand. Next, considering the seasonal variations in demand and supply, the performance of DHS is simulated using a hydraulic model and evaluated through a cost-benefit analysis. For evaluating the effect of land-use policy, several scenarios are designed to reflect the redistribution of heat demand. Finally, comparing with the different results obtained for these scenarios, the crucial factors and best policy pathway were identified. With respect to the sources for the data used, this study refers to many reports and surveys conducted during the project, and also utilized data sources such as building point data from ZENRIN (2014) and ArcGIS Data Collection of Japan supported by ESRI (2015).

3.2. Network design and simulation

Since this study proposes to recover and utilize waste heat from multi sources, and supplying heat over a much dispersed urban area, a multi-source district heating network is designed based on GIS database and hydraulic calculations. Usually, such a network has a hierarchical structure similar that shown in Fig. 7. Corresponding to the distance from the heat sources and concentration boundary of heat demand, the supply area is rezoned and controlled using substations. The flow rate, which relates to the rate of heat transport, is adapted in real-time to the variations in heat demand by the substations.

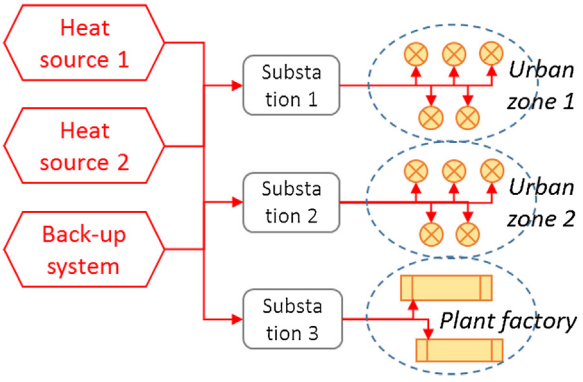

Fig. 7. The structure of multisource district heating network.

Accordingly, the design process of a pipeline network includes two parts that are shown in Fig. 8. One is to enable the design of the spatial layout by GIS spatial analysis, and the other one is to decide the diameter of pipeline for each segment. From the data obtained for the distribution of heat demand and supply, the structure of the heating network is decided. Next, referring to the local topography and road network, the detailed pipeline layout is drawn following the principle of the shortest route analysis (for minimizing pipeline costs). Next, for each segment of pipeline, the length and peak season heat load are derived and these values are used as input into the hydraulic model for diameter design and performance simulation. The detailed formulation is summarized below.

(a) Design conditions

Generally, hot water is chosen as the heating medium. Usually, in Japan, the supply temperature of the heating medium and the temperature difference on the user side are set as 80 and 20 °C, respectively (DHCJP, 2014). Commonly, a single steel tube and glass wool are chosen as conduit and heat insulating material respectively, and the pipeline is assumed to be laid underground for protecting urban landscape. Then due to the peak season demand in winter, we calculate appropriate diameter of pipeline and return the result of required pumping power for heat transportation.

(b) Pipeline diameter

On the basis of the abovementioned assumptions, the relation between the peak season heat demand Q_d of each pipeline segment, the volume flow rate V_v is written as follows

$$V_v = \frac{Q_d}{C\rho t \cdot \Delta T}, \tag{1}$$

where C is the specific heat capacity of water, ρ is the density of water, t is operation time and ΔT is the temperature difference on the user side. Then inner diameter is calculated as follows:

$$d = \sqrt{4V_v/\pi v} \tag{2}$$

where v is the average flow rate set as 2 m/s for avoiding corrosion inside the pipelines.

(c) Pressure drop

Due to the friction between water and the pipeline, there is a pressure drop ΔP in heat transport that needs a certain pumping power to complement this resistance. On the basis of the Darcy–Weisbach equation, the pressure drop is calculated pipeline with length l of a pipeline segment as

$$\Delta P = \lambda \cdot \frac{2l(1+k)}{d} \cdot \frac{v^2}{2}\rho, \tag{3}$$

where k is the local resistance ratio and the frictional coefficient λ is given by

$$\lambda = 0.0055 \cdot \left| 1 + \left(20,000 \frac{\varepsilon}{d} + \frac{10^6}{Re} \right)^{1/3} \right|, \tag{4}$$

where ε is the equivalent roughness of the pipe wall (set as 0.045 mm) and Re is the Reynolds number. Then the necessary pumping power W' is estimated as follows:

$$W' = \frac{\rho g V_v h}{\eta_P \eta_M}, \tag{5}$$

where $h = \Delta P/\rho g$ is the pressure-head loss, g is gravitational acceleration, η_P is the efficiency of the pump, and η_M is the efficiency of the motor. According to Wei (2003), η_P and η_M is set as 0.7 and 0.9, respectively.

(d) Temperature drop

The temperature drop, which leads to the heat loss, ΔT_l is an important indicator and is estimated as follows:

$$\Delta T_l = (T_\omega - T_a) \cdot \exp\left(-\frac{1}{CV_w(R_s + R_p)} \right), \tag{6}$$

where T_ω is the supply temperature, T_a is the temperature of the soil surface (average 13 °C in Fukushima Prefecture), V_w is the weight flow rate, R_s is the soil heat resistance, and R_p is the heat resistance of the pipeline.

(e) Constraint condition

Physically, the actual heat supply quantity Q_s should be not greater than the potential of waste heat supply marked as $\hat{Q}_s$, but is equal to the sum of the heat demand Q_d and the heat loss Q_l as follows:

$$Q_s = Q_d + Q_l, \quad Q_s \le \hat{Q}_s. \tag{7}$$

Finally, considering that the heat demand is intimately related to the outside temperature, we have divided one year into two periods to identify the seasonal variations in demand and supply: from May to October and from November to the following April. The ratios of the heat load between the former and the latter are, respectively, 35% and 65% for civilian sector and 0% and 100% for greenhouse type plant factory (the data on the demand variation is available from JIE (2008)). Consequently, the pipeline network is designed to accommodate the peak period demand and assumed to be appropriate for the whole year.

3.3. Cost-benefit assessment

According to the literature (Nielsen and Moeller, 2013; Persson and Werner, 2011), generally the economic costs should include heat distribution cost C_d (infrastructure construction), heat transport cost C_t (pumping power), heat production cost C_p, and management and maintenance cost C_m. The benefits include revenues from heat sales (subsidies are not considered for the moment). This study adopts a more comprehensive understanding on the socioeconomic benefits targeted toward a total reduction in fuel cost (covering production cost and heat sale revenue), and includes environmental benefits, i.e., total CO_2 emission reduction. The cost is formulated as

$$C = C_d + C_t + C_m, \tag{8}$$

$$C_d = a \times \sum_n c_n \cdot l_n, \quad \text{and} \tag{9}$$

$$C_t = (a \cdot c_w + p^e \cdot t) \times W', \tag{10}$$

where c_n and l_n are the average cost and length of pipe with diameter n, respectively. c_w is the average cost of the pumping equipment, p^e is the price of electricity, and t is the operation time. a is the annuity rate that is defined as

$$a = \frac{i}{1 - (1/(1+i))^\tau}, \tag{11}$$

where i is the interest (set as 1.15%) and τ is durability in number of years (set as 20 years, as the same as operation period). It follows that the benefit of fuel cost reduction R_f and CO_2 reduction R_{CO_2} are calculated as below:

$$R_f = \sum_i q'_i \cdot p_i \tag{12}$$

$$R_{CO_2} = \sum_i q'_i \cdot \varepsilon_i - W' \cdot t \cdot \varepsilon_e \tag{13}$$

where q'_i is the fuel substitution of type i, p_i is the price of fuel type i, ε_i is the emission unit of fuel type i, and ε_e is emission unit of electricity. Management and maintenance costs are considerably flexible among companies, this study assumes that this is a fixed amount including labor, sales service, and general maintenance costs. This value is set to be 37 million yen annually in view of results from a similar case in Hitachi Station area of Ibaraki Prefecture, which uses industrial waste heat to supply the railway station area.

Regarding the assessment of the environmental impact, this consists of the CO_2 emission from the construction of infrastructure and the electricity consumption of the water pump, from which the advantages due to reduction in emission due to fuel substitution are subtracted. Referring to Togawa et al. (2009), the CO_2 emission unit of pipeline construction is 78 kg/m by LCA and since this value is considerably small when compared to the emission arising from the pumping during its operation period of decades, this is omitted for the current calculation. However, in the future, we expect to conduct a LCA evaluation on the entire project to evaluate the actual environmental impacts. According to the report of Tohoku Electric Power Company, the emission unit of grid electricity and fuel oil consumption in 2013 are 163.61 and 67.78 t/TJ, respectively.

It is, however, assumed that currently the residents in Shinchi Town use high-efficiency electrical air-conditioners (heat pump type) for space heating and water heaters powered by LP gas for hot water. Plant factory is assumed to use fuel oil boiler for space heating. The main parameters relating to the cost and CO_2 emission estimation are summarized in Appendix b.

3.4. Scenarios setting

Although the survey shows that a large amount of waste heat is available for urban area use by I-US design, most of the area in Komagamine has a heat demand density even lower than 50 TJ/km^2 (generally 420 TJ/km^2 is thought as the minimum heat density required by DHS in Japan), the feasibility of introducing DHS is doubtful in the current situation. Two approaches can be considered to improve the feasibility: one is to increase the waste heat usage by guiding energy intense factories or agricultural units such as plant factory to locate near the park, and the other is to promote

a compact land use in the residential areas to reduce pipeline costs. Both are currently available in Shinchi Town, since the greenhouse type plant factory is a regular feature in Northeastern Japan and compact urban development has already become a national policy due to the Low-carbon Urban Development Law of Japan passed in 2012.

To assess the impacts of introducing DHS using waste heat by different land use policies, four scenarios are set to reflect the four extreme situations. The contents of the four scenarios are summarized as below:

- **Business as usual (BAU)**: Directly introduce DHS using waste heat into Komagamine, and no specific land use policy is implemented;
- **Green agriculture**: Directly introduce DHS using waste heat into Komagamine, with guidance to locate newly built plant factories near the industrial park to use the redundant supply;
- **Compact land use**: Promote compact land use in Komagamine while introducing DHS using waste heat from industries;
- **Green development**: Promote compact land use in Komagamine while introducing DHS using waste heat from industries, and guide the location of newly built plant factory to use the redundant supply.

To ensure that all these scenarios are realistic, the heat consumption unit of the plant factory is set with reference to a local plant factory in Shinchi Town and the compact land use indicator is set with reference to a similar project in Kobunaki Eco-Town of Shiga Prefecture. Moreover, several assumptions are made for achieving a variable control:

- Total population and floor area in the location of case study, energy consumption intensity and the energy price are assumed to not change significantly in the short term;
- All the users in case area prefer to connect to the DHS network rather than individual heating, because of the attractive price of heat purchase;
- No epoch-making technology revolution in individual or district heating during the time period of this study. COP (Coefficient of Performance, defined as the ratio of energy for heating or cooling divided by work required) of the air conditioner is set as 7.0, efficiency of water heater and fuel oil boiler are set as 0.95 and 0.9, respectively (CRDS, 2013). These parameters are set higher than current values considering the general availability of high efficiency technology in near future.

Since geographic proximity is a crucial factor for I-US design, we try the best to localize the demand site close to the industrial park. As far as residential areas are concerned, we have proposed to limit the location of the households into the area between the entrance to the industrial park and Komagamine Station, by increasing population density from current 800 to 8000 person/km^2 (Kobunaki Eco-Town level); for the plant factory, we propose to utilized the farmland north of the industrial park, which has at least more than 0.5 km^2 available area. The image of the spatial layout for each scenario is mapped in Fig. 9.

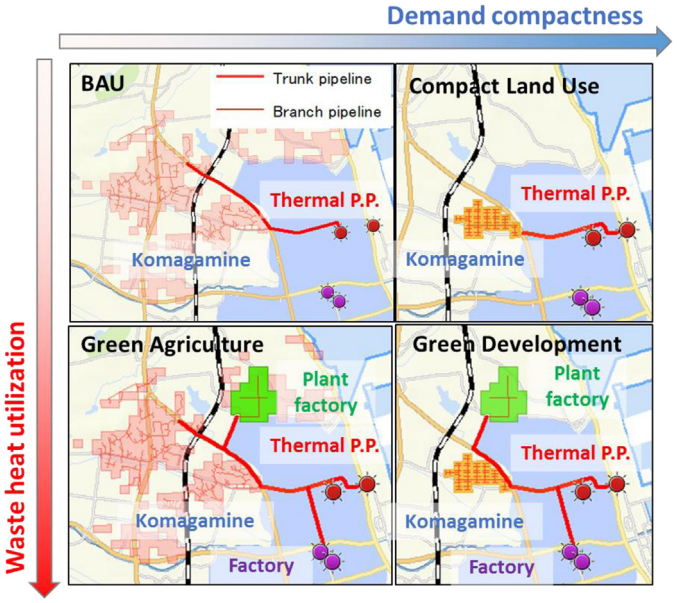

Fig. 9. Land use design of scenarios.

In the BAU and Green Agriculture scenarios, the pipeline network is designed along the road branch by the shortest route analysis, while in Compact Land Use and Green Development scenarios the pipeline is designed following feasible and efficient *T-connection* pattern (Dalla Rosa et al., 2012). Due to the different land use patterns in these scenarios, there is a baseline for each scenario that shows the total energy demand, CO_2 emission and fuel cost before the introduction of DHS. The main parameter differences are summarized in Table 1.

4. Result and discussion

4.1. Result of scenario analysis

On the basis of the scenario setting, we assess the performance of DHS and summarize the result in Table 2. When environmental performance is considered, all the scenarios seem to reduce CO_2 emission in the future. Green Development realizes the largest reduction of approximately 2800 t CO_2 emission annually which is 35% of the total baseline emission, while the least reduction is for the BAU scenario that achieves a 300 t reduction which is 7% of the total in the baseline scenario (current individual heating). Approximately 2600 t of extended CO_2 emission reduction comes from the location of the plant factory. However, when economic performances are considered, only Green Development realizes an annual net revenue of 40 million yen. Although the close location of the plant factory brings approximately 50 million yen of addi-

Table 1
Comparison of main parameters between scenarios.

Indicator	BAU	Green agriculture	Compact land use	Green development
Land area[a] (km^2)	1.11(0)	1.16(0.05)	0.20(0)	0.24(0.04)
Annual energy demand[a] (TJ)	47(0)	79(32)	62(0)	91(28)
of which heat demand[a] (TJ)	17(0)	47(30)	23(0)	51(27)
Annual CO_2 emission[a] (t)	4453(0)	7035(2581)	5864(0)	8180(2316)
Annual fuel cost in case of individual heating[a] (million yen)	222(0)	314(92)	295(0)	378(82)
Pipeline length[b] (km)	17.9(15.9)	19.7(15.9)	6.8(6.0)	9.2(6.0)

[a] Data in parenthesis is the quotient of the plant factory.
[b] Data in parenthesis is the quotient of branch line.

Table 2
Result of scenario analysis.

Scenario	BAU	Green agriculture	Compact land use	Green development
Annual usage of waste heat (TJ)	24	56	27	56
Overall rate of heat loss	29%	14%	13%	8%
Annual operation time (h)	8760	8760	8760	8760
Annual net revenue (million yen)	−135	−69	−12	41
Annual CO_2 reduction (t)	313	2620	761	2814
Pay-back period (year)[a]	–	–	–	12

[a] Investment on facilities and pipelines divided by annual cash flow (without subsidies). "−": over the preset operation period (20 years).

tional income from sales, the policy of promoting compact land use reduces much more cost (approximately 110 million yen per year) by reducing the investment in infrastructure and equipment. Since compact land use and proximate location of plant factory are not in conflict, to realize a co-benefit of economy and environment, the best policy is to combine these two aspects for maximizing the advantage of DHS using waste heat.

4.2. Policy pathway

Since the four scenarios represent four extreme situations, theoretically, the actual future of policy implementation should be within the limits between four scenarios (Fig. 10). Moreover, although Green Growth is the best choice, the way this policy is implemented will impact the cost and benefit of the project. For a cursory analysis, we assume that the priorities of the land use policy can be described by the following two possibilities:

- Pathway A: The budget is insufficient so that the promotion of compact land use is given the priority, following which DHS is introduced gradually to adapt to the increasing heat demand density;
- Pathway B: Budget is sufficient to speed up the substitution of individual heating by district heating.

Clearly, since there is a trade-off between economic and environmental benefits, in the case of an insufficient budget, it is better to first relocate residents so as to concentrate the households near the industry before beginning the construction of district heating network. This option leads to lower total cost but also to less reduction in CO_2 emission. In contrast, in case of an unlimited budget, e.g., the availability of external funding for environmental improvement, introducing DHS at early stage is definitely more efficient and will lead to more reduction in CO_2 emission. Although the two different pathways will lead to the same result, that is, toward Green Growth during the time period of policy implementation,

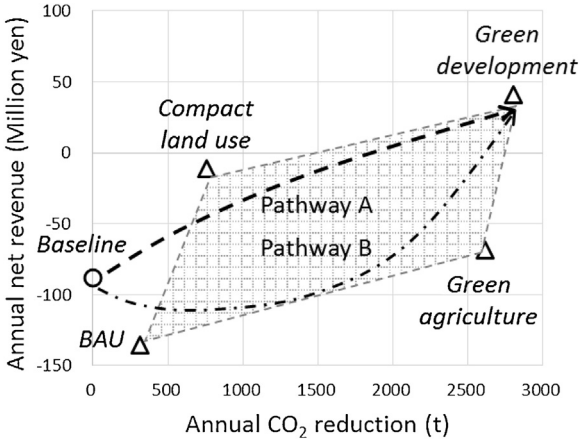

Fig. 10. Result of scenarios and policy pathway.

the accumulated economic cost and CO_2 reduction is quite different for the two cases. In the case shown in Fig. 10, roughly, the pathway B reduces approximately 10,000 t CO_2 more than pathway A, but it increases the total cost by 500 million. In the sense of a carbon market, the average price of reducing CO_2 in this case is approximately 50,000 yen/t. This aspect could be further discussed in business models and financial systems such as introducing CDM (Clean Development Mechanism), PPP (Public-Private-Partnership) for the project (Wand et al., 2016).

4.3. Sensitivity analysis

As a first step trial, this study constructs a static model and assumes that all the factors remain invariant except for land use. In fact, according to the local master plan of Shinchi Town and market trends, several critical factors including waste heat supply are very likely to change in the future. According to the survey and negotiation to the companies, it reveals that the companies of thermal power plants will try to recover more waste heat, if economic benefit is actually realized by current practice. Otherwise, as mentioned in Section 2, Shinchi Town carried out a master plan to increase population to 10,000 persons in 2015 which means a 2000 increment from 2014 level. Shinchi Station area and Komagamine area, where are recognized as two pilot redevelopment area, are expected to accommodate the increasing population. Finally, energy price is also a variable which is predicted to increase a lot in the future. To test the sensitivity of results, we further add three external scenarios defined as follows.

- Aiming at achieving more economic benefit, thermal power plants decide to increase the heat supply by 30% through expanding the capacity of heat exchangers;
- In the future, large scale LNG base construction and industrial development attracts approximately 1000 migrants to "Eco-Village" Komagamine;
- Due to the carbon tax and global fossil fuel price increase, energy price in Japan continues to increase and reaches two times the current value.

The impacts of these three assumptions are summarized in Fig. 11. Clearly, the more the heat supply increases, the larger could be the scale of plant factory. In contrast, limited by the maximum supply quantity, increasing the heat demand in urban areas offsets the attractiveness of the plant factory, but improves the economic balance. Predictably, the energy price could increase a lot in the future that would significantly increase the economic benefit of energy saving. Consequently, even in a low heat demand density area, as a long-term vision, introducing DHS could be a priority selection if we follow the global trend and implement the relevant land use policies. This should lend a strong support to making DHS more popular.

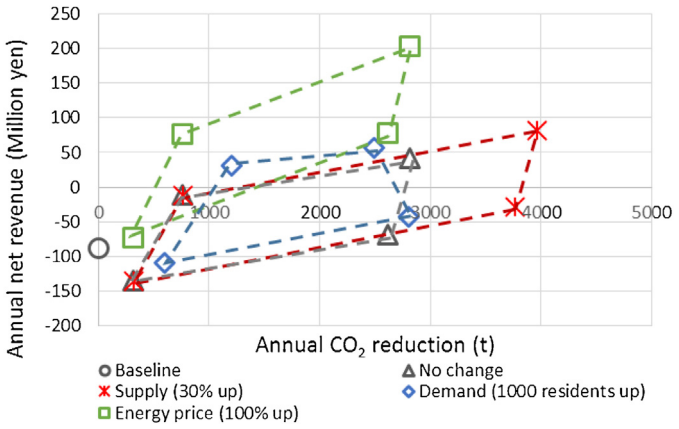

Fig. 11. Sensitivity analysis.

4.4. Discussion

On the basis of these results, we identify several key points concerning the promotion of DHS using waste heat.

Firstly, Energy Symbiosis, which is specified from I-US, has a significant potential to reducing fuel consumption and CO_2 reduction. However, these effects are considerably dependent on the quality and quantity of heat demand, the distance to heat sources, and energy prices. Low and dispersed heat load will increase the length of pipeline and pumping power by a large factor, which leads to a corresponding increase in construction cost and in turn increase CO_2 emission from electricity consumption. Therefore, even though waste heat recovery will save fuel purchase cost comparing with boiler-based or gas cogeneration-based DHS naturally as a low-carbon heat source, we have to pay attention to early stage symbiotic design, so as to confirm and strengthen the advantage of DHS using waste heat than individual technologies.

Second, although theoretically, the usage of waste heat in district heating could enhance its competitiveness in low density areas, the actual performance is determined by the local land use pattern. This aspect makes it an ideal case for highlighting the symbiosis design. In low-density areas, symbiosis design on land use could radically turn losses into gains, which makes the popularization of DHS feasible. However, it is necessary to integrate such energy system design from an early stage of decision making. Along with the worldwide tendency to have a compact urban development, e.g., *Transit-oriented Development*" (Calthorpe, 1993; Cervero, 1998; Hayashi et al., 2011), now is the right time to embed DHS plan into urban planning schedule.

Third, policy implementation path is as an important factor to the overall CO_2 reduction and optimizing cost. Since several years or a decade is necessary to implement land use policies, the recommendations to ensure compact land use or changing the location of energy intensive demanders will bring about a significant difference. In the abovementioned case study, an additional investment of 500 million yen for speeding up the introduction of DHS may bring about a reduction of an additional 10,000 t of CO_2 emission. Furthermore, sensitivity analysis also implies that in the future, increasing waste heat supply from power plants, increasing demand from new migrants, and rising energy prices, could greatly enhance the benefits of economy and environment. In short, the policy maker is encouraged to look more positively and with more ambition in planning such a strategy.

5. Conclusion

Energy shortage and global climate changes have created challenges for the world, especially Japan. The most effective approach is to reduce energy consumption while reducing the dependence on fossil fuels. Popularizing DHS using waste heat is shown to be as an attractive solution; however, currently, there are still negligible cases in Japan, and even these are only available in districts with a highly concentrated heat demand. One important reason for this is the lack of a viable land-use policy for promoting the usage of waste heat. To scientifically and quantitatively evaluate the improvement brought about by land use policies on the feasibility and efficiency of introducing DHS using waste heat, this study combines both system design and land use design into a symbiosis network development, to conduct a cost-benefit analysis based on inventory survey and geographic database. Shinchi Town of Fukushima Prefecture, which suffered from the Great Eastern Japan Earthquake but has a high potential for the generation of industrial waste heat, is chosen as a case study. The result shows that although the direct use of introducing DHS could reduce CO_2 emission by 313 t annually, a large deficit of 135 million yen per year cannot be avoided. Considering this situation, this study proposes two land-use policies; including one that increases waste heat usage through proximate location of plant factories and the second by enhancing the heat demand density through compact urban planning. Obtained results from these scenarios indicate that the compact land use policy greatly reduces cost by shortening the length of pipelines, while judicious location of plant factories can bring about much more CO_2 reduction. The most efficient decision is to combine these toward the best prospects (Green Development), namely, annually 41 million yen net revenue with 2800 t CO_2 reduction.

As a first step trial, this study simplifies many technical factors to focus principally on investigating the impacts from land use policies. This study considers only power plants and factories as potential waste heat sources, and uses seasonal demand variation for network design. In fact, the current low temperature District Heating System can also connect with many heat sources such as heat from biomass, underground, or river. Moreover, daily demand variation in different seasons should be used for network optimization. In future work, the model framework would be improved to include these factors. Furthermore, since both individual heating and district heat technology will be improved, and the socioeconomic factors will change in the future, for actual decision making, these changes should also be reflected in the analysis of the different scenarios. Nevertheless, it is expected that the results from this study could be a valuable support material for sustainable urban planning and decision making.

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Appendix.

a.. Estimation of heat demand

The formula for estimating heat demand by floor area method is defined as follows:

$$Q_d = \sum_{i,j} A_{i,j} \times u_j \quad \text{(A1)}$$

where Q_d is the sum of annual heat demand of buildings in an area, $A_{i,j}$ is the floor area for purpose j in building i, and u_j is the average consumption unit by floor area for purpose j. The data on heat demand units used herein is summarized in Table 3.

Table 3
Energy consumption unit by building types and purposes.

Type	Unit	Electricity	Cooling	Heating	Hot water
Detached house[a]	MJ/m^2 y	67.1	1.0	61.6	55.1
Collective house[a]	MJ/m^2 y	79.0	1.2	72.6	64.8
Office[b]	MJ/m^2 y	561.6	293.0	129.6	9.4
Shop[b]	MJ/m^2 y	813.6	523.0	146.5	96.1
Hotel[b]	MJ/m^2 y	720.0	418.7	334.8	334.8
Hospital[b]	MJ/m^2 y	612.0	334.8	309.6	334.8
Plant factory[c]	MJ/m^2 y	30.1	0	555.0	0

[a] Local average value estimated by the author.
[b] National average value estimated by JIE (2008).
[c] Survey value of a local typical plant factory (Togawa et al., 2014).

Table 4
Cost of pipeline and pump equipment.

Item	Value
Average piping cost (trunk)	150,000 yen/m
Average piping cost (branch)	60,000 yen/m
Average pumping cost	36,800 yen/kW

Data source: Market survey.

Table 5
Fuel price and CO_2 emission unit.

Fuel type	Price	CO_2 emission
System electric power		163.61 t/TJ
(household)	24.9 yen/kWh	
(business)	15.3 yen/kWh	
LPG	7.08 yen/MJ	59.03 t/TJ
Fuel oil (A type)	2.44 yen/MJ	69.30 t/TJ

Data source: Published data from the Tohoku Electric Power, the Oil Information Center, the Agency of Natural Resources and Energy, and the Ministry of Environment, Japan.

b.. Cost and efficiency parameters

Main parameters relating to cost and CO_2 emission are listed in Tables 4 and 5. The average price of pipeline construction is estimated from a quotation from a local engineering company, including all the costs such as material cost, labor cost, consumption tax, and design fee.

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